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NSWC TR 88-340

AD-A207 409

# NITINOL-BASED FUZE ARMING COMPONENT

BY DAVID GOLDSTEIN AND ENS ALEX WEINER

RESEARCH AND TECHNOLOGY DEPARTMENT

OCTOBER 1988






**NAVAL SURFACE WARFARE CENTER**

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# REPORT DOCUMENTATION PAGE

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED | 1b. RESTRICTIVE MARKINGS |
| 2a. SECURITY CLASSIFICATION AUTHORITY | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution is unlimited. |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>NSWC TR 88-340 | 5. MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Naval Surface Warfare Center<br>6b. OFFICE SYMBOL (If applicable)<br>Code R32 | 7a. NAME OF MONITORING ORGANIZATION |
| 6c. ADDRESS (City, State, and ZIP Code)<br>10901 New Hampshire Avenue<br>Silver Spring, MD 20903-5000 | 7b. ADDRESS (City, State, and ZIP Code) |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c. ADDRESS (City, State, and ZIP Code) | 10. SOURCE OF FUNDING NOS.<br>PROGRAM ELEMENT NO. 0602315N; PROJECT NO. RP15S66; TASK NO. 40104; WORK UNIT NO. 9U41QC |
| 11. TITLE (Include Security Classification) NITINOL-Based Fuze Arming Component | |
| 12. PERSONAL AUTHOR(S)<br>Goldstein, David and Weiner, ENS Alex | |
| 13a. TYPE OF REPORT<br>13b. TIME COVERED FROM _____ TO _____ | 14. DATE OF REPORT (Yr., Mo., Day)<br>1988, October<br>15. PAGE COUNT<br>35 |
| 16. SUPPLEMENTARY NOTATION | |

| 17. COSATI CODES | | |
|---|---|---|
| FIELD | GROUP | SUB. GR. |
| 11 | 06 | 01 |
| 19 | 01 | |

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

NITINOL, Shape Memory Alloys, Fuze, NiTi, Safing and Arming, Nickel Alloys, Titanium Alloys, (Ni-Ti)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

NITINOL Shape Memory Alloy wire was strained to increase its first-time transformation temperature to as high as 150°C. The useful work done by a wire, within limits, is a function of the strain in it. Strains residual from the annealing process and those introduced after annealing can greatly affect the first time transformation. The load lifted and extent of contraction can be varied inversely for a given wire. The energy required for heating and transformation was a function of the work performed, varying between 60 and 144 Joules per gram for the 1/4 mm (0.010 inch) wire used in this work. It is concluded that NITINOL can be used for Safing and Arming components.

Under no-load conditions NITINOL can recover 6.5 percent strain at 360°C.

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|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>__UNCLASSIFIED/UNLIMITED X SAME AS RPT. __DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>David Goldstein | 22b. TELEPHONE NUMBER (Include Area Code)<br>(301)394-2468<br>22c. OFFICE SYMBOL<br>R32 |

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted
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## FOREWORD

NITINOL shape memory alloy was investigated for use as the active element of a Safing and Arming subsystem of a fuze. Obtaining a substantial shape memory effect under load, at a suitable temperature and with a minimum energy requirement, was a primary objective. Increased strain was used to increase the temperature for first-time transformations in this shape memory alloy. This phenomenon was presented in two prior technical reports (NSWC TR 86-196 and NSWC TR 87-126) and is expanded on in this study.

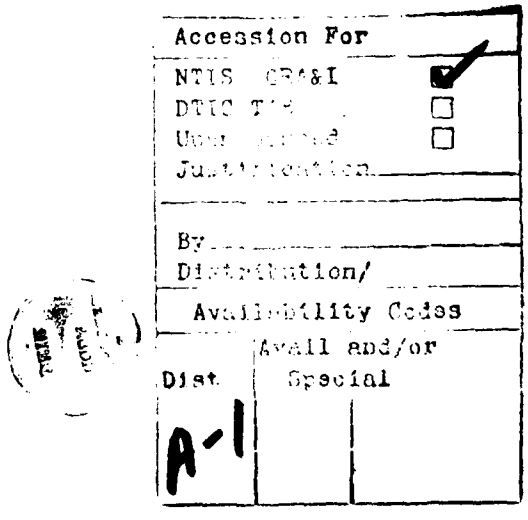
The authors acknowledge the very significant contributions of Dan Lenko in achieving the substantial progress made toward the objective. The noteworthy technical contributions of John Scarzello, Gary Burak, and Ed Morai are also gratefully acknowledged.

This study was funded under Navy Program Element 0602315N.

Approved by:

Carl Mueller

CARL MUELLER, Head
Materials Division



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## BACKGROUND

Fuzes are used in explosive devices to permit their detonation at the appropriate time. The fuze subsystem that prevents premature detonation and subsequently enables the detonation to proceed is a safing and arming (S&A) device. Arming includes a physical movement within the fuze so that the explosive train is aligned and able to function.

The concept of using the shape memory phenomenon of NITINOL alloys for arming has intrigued designers for many years. One concern has been that available alloys activate at approximately 100°C, which is considered marginal for all-weather operations. Attempts to raise this temperature by changing the composition of the shape memory alloy[1,2] have been only partly successful.

Internal strains substantially raise the transformation temperature of NITINOL shape memory alloys in their first transformation following straining.[3-5] This phenomenon was exploited in the current work.

A fuze design developed at this Center[6] presented a simple method for electrically actuating a NITINOL-based S&A component. This design, together with the higher temperatures achievable by straining the NITINOL, were the basis for performing the experimental work reported here.

## INTRODUCTION

The generalized requirements for a S&A device based on actuation of a NITINOL wire follow. The device must be of minimal volume and weight. It must meet applicable safety standards,[7] and be responsive to electrical activation. The stored energy package for activation must be within the state of the art. The device must function over a wide band of ambient temperatures.

The tasks specifically addressed in developing the basis for the new device were: (1) to activate the NITINOL at appropriate temperatures, (2) to determine the energy required for its activation, (3) to determine the force it exerts, and (4) to determine the movement it generated while exerting that force.

An operating model was constructed to demonstrate the feasibility of using a single NITINOL wire acting in a simple stretching and contracting mode. Conflagration safing and shock resistance measures were not built into this model, although there are simple schemes by which this can be done.

## EXPERIMENTAL PROCEDURES

The NITINOL wire was prepared from a single melt, Heat 83825. This binary alloy was induction melted to a nominal composition of 54.7 weight percent nickel, balance titanium. It was hot forged, hot swaged, and then drawn into wire at room temperature. Its transition temperature range for good shape memory response, under no-load conditions, is 80 to 100°C. The wire specimens in this work were primarily 1/4 mm (10 mil) in diameter and 25 cm in length.

NITINOL alloys activate, i.e., they can show shape memory effects, when their crystal structure transforms from a martensitic to an austenitic phase during heating. Since strain significantly changes the temperatures of the transformation, these temperatures were determined using pre-strained wires lifting various loads. The test conditions emulate those desired for a prototype S&A device. The data were obtained under load conditions using the furnace arrangement shown in Figure 1.

The transformation energy was measured with the equipment presented schematically in Figure 2.

The operable model demonstrating concept feasibility was based on the schematic shown in Figure 3(a). The slide plate, which can move easily along the plate guide, and the frame are Micarta. When the 9 volt battery pulses the NITINOL wire it contracts, retracting the pull pin (shown in the magnified view). This action removes the interference to the slide retaining pin. The compressed spring behind the slide plate then propels the slide plate very rapidly to its final position as shown in Figure 3(b). The firing pin opening is now positioned to let the explosive lead function.

This model was operated successfully numerous times at ambient temperature, with transformation of the same wire occurring at a temperature between 80°C and 100°C. The electrical pulses were of unknown duration but estimated to be about 1 second.

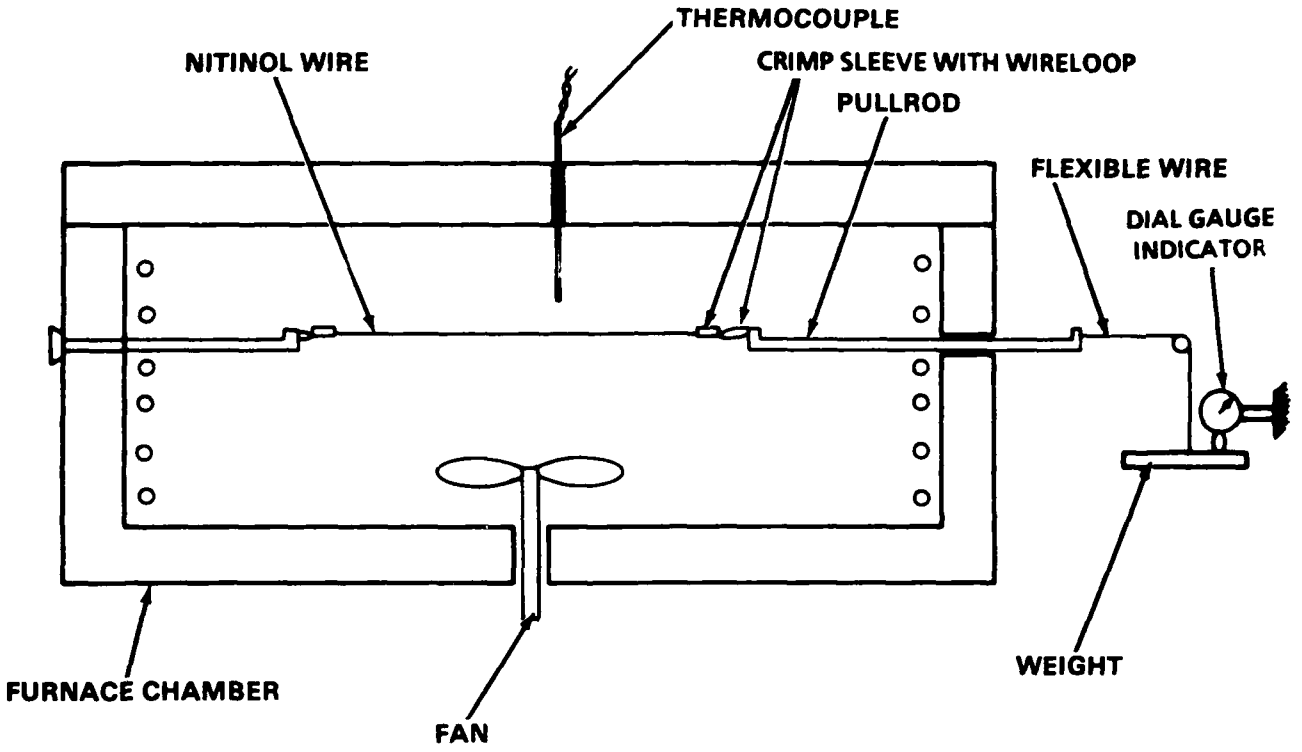
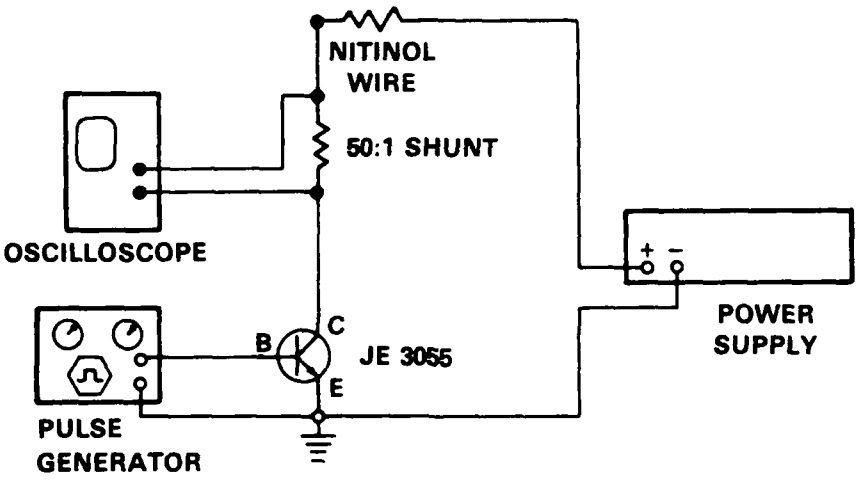



FIGURE 1. FURNACE APPARATUS FOR DETERMINING CONTRACTION OF NITINOL UNDER LOAD




FIGUR E 2. ELECTRICAL SCHEMATIC OF APPARATUS FOR DETERMINING ENERGY TO TRANSFORM NITINOL WIRE

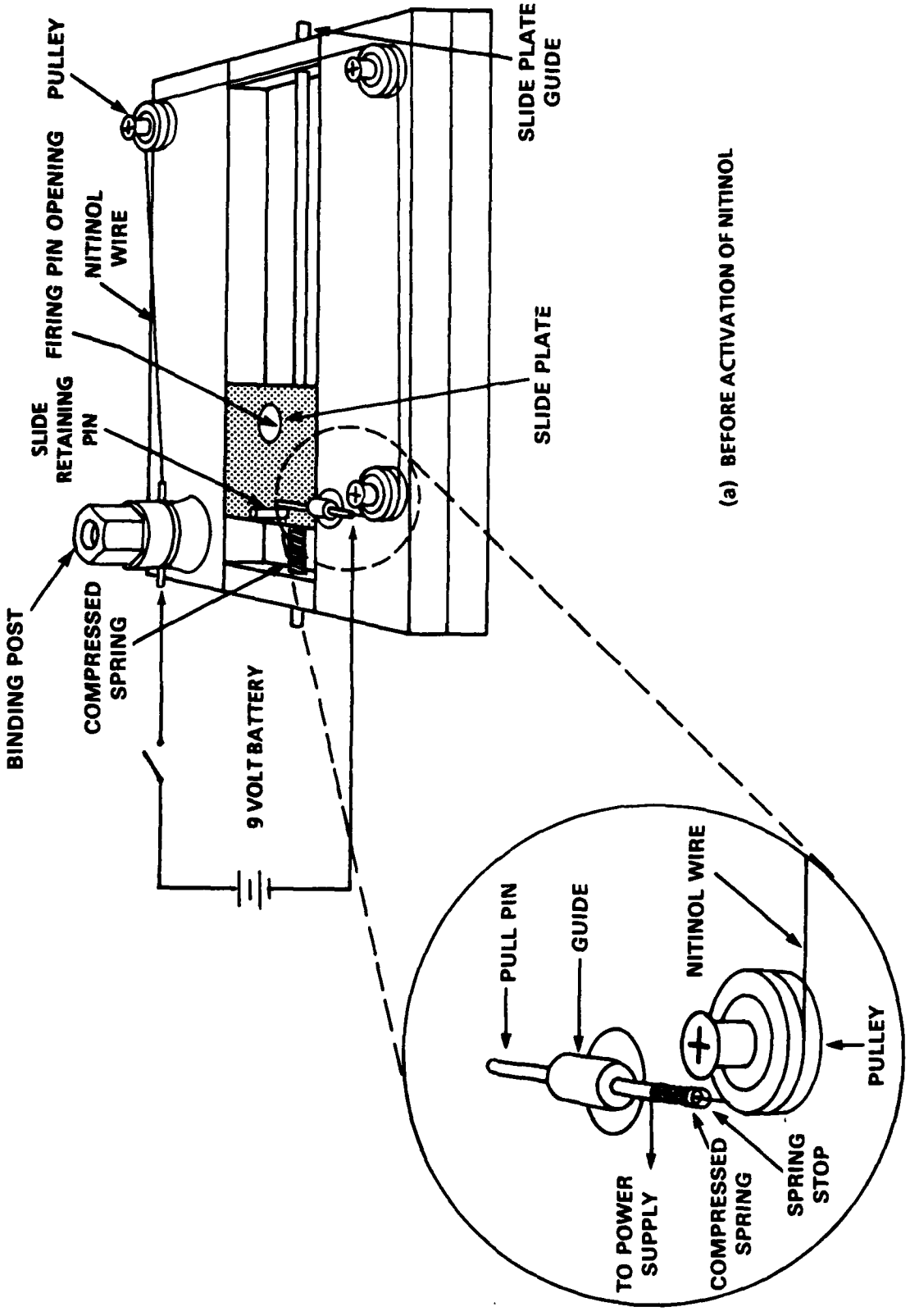
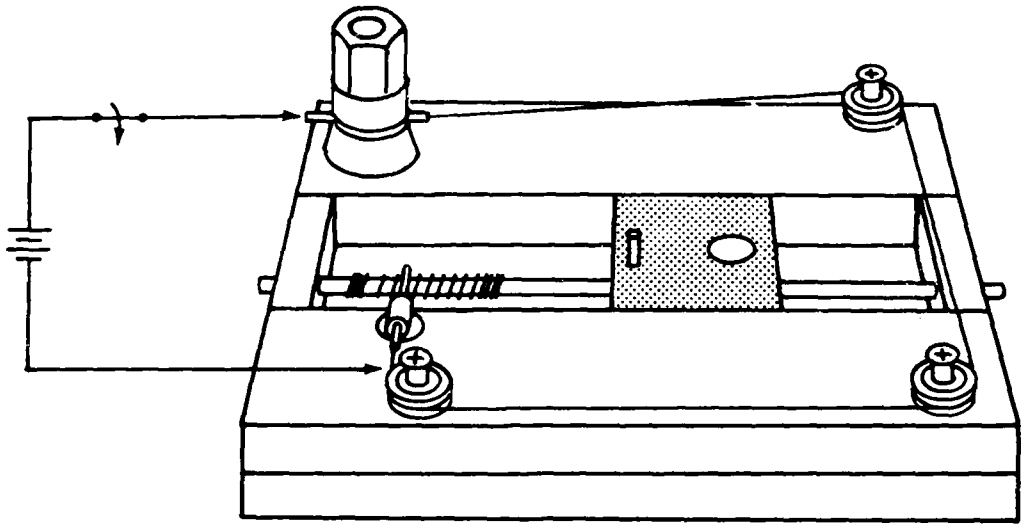



FIGURE 3. FEASIBILITY DEMONSTRATION MODEL



(b) AFTER ACTIVATION OF NITINOL

FIGURE 3. (CONT.)

## EXPERIMENTAL RESULTS AND DISCUSSION

### TEMPERATURE OF ACTIVATION

Since strains are a major factor in raising the transformation temperatures of NITINOL, some discussion of them is appropriate. Three different souces generated the significant strains that influenced our results. The magnitude and direction of their vector resultant is the net strain that determines the temperature and extent of shape recovery on the first heating. The sources of these strains, and their individual contributions to the shape memory transformation, are discussed below.

Historically, the first source of strain is the wire drawing process. If the final annealing treatment does not completely remove this strain, then the residual amount will affect the completeness and temperature of all subsequent shape recoveries. This is a permanent strain, and only further annealing will remove it.

The substantial residual strain in an as-drawn wire will contract it in length about 3 percent upon its first heating[3] to 360°C. The effect of residual strain on the transformation of an as-drawn wire that was partially annealed is shown in Figure 4. This wire, strained 7.6 percent after annealing, shows a shape recovery of 2.4 percent (as a contraction), begining at 100 and ending at 140°C, upon its first heating. Pre-strain (to be discussed later) and residual strain jointly determine this transformation temperature. The stresses associated with the residual strain then produced the additional 4.0 percent contraction during heating of the wire from 140 to 360°C. Details of the experimental procedure are given in Appendix A.

If adequate energy is available to quickly produce a temperature of 360°C in a NITINOL wire, it will be a viable high temperature, fast, single-use, large movement (6.5 percent) actuator for light duty service. Alternatively, it may be useful as a rapidly acting sensor to detect flash heating conditions.

Historically, the next source of strain is the tensile extension (stretch) of the wire following the annealing treatment. This pre-straining is done to elongate the wire so that there is considerable shape recovery (contraction) upon heating. Extensions greater than 4 percent induce some permanent strain,[8] and above 6 percent it is palpable as strain hardening.

If no permanent strain exists in a wire, i.e., it is fully annealed, (850°C, 1 hour, furnace cooled) and the pre-strain is less than 4 percent, then shape recovery occurs on the first heating to 150°C, with no further shape change between 200 and 400°C. Without the residual and +4 percent pre-strains, however, shape recovery under no-load conditions is only 70 percent of the original deformation. This is inferior recovery, as compared to a wire with both residual and pre-strain. Unrecovered pre-strain is a permanent strain, which is measurable as a non-recovery of shape, and is superimposed on residual strain.

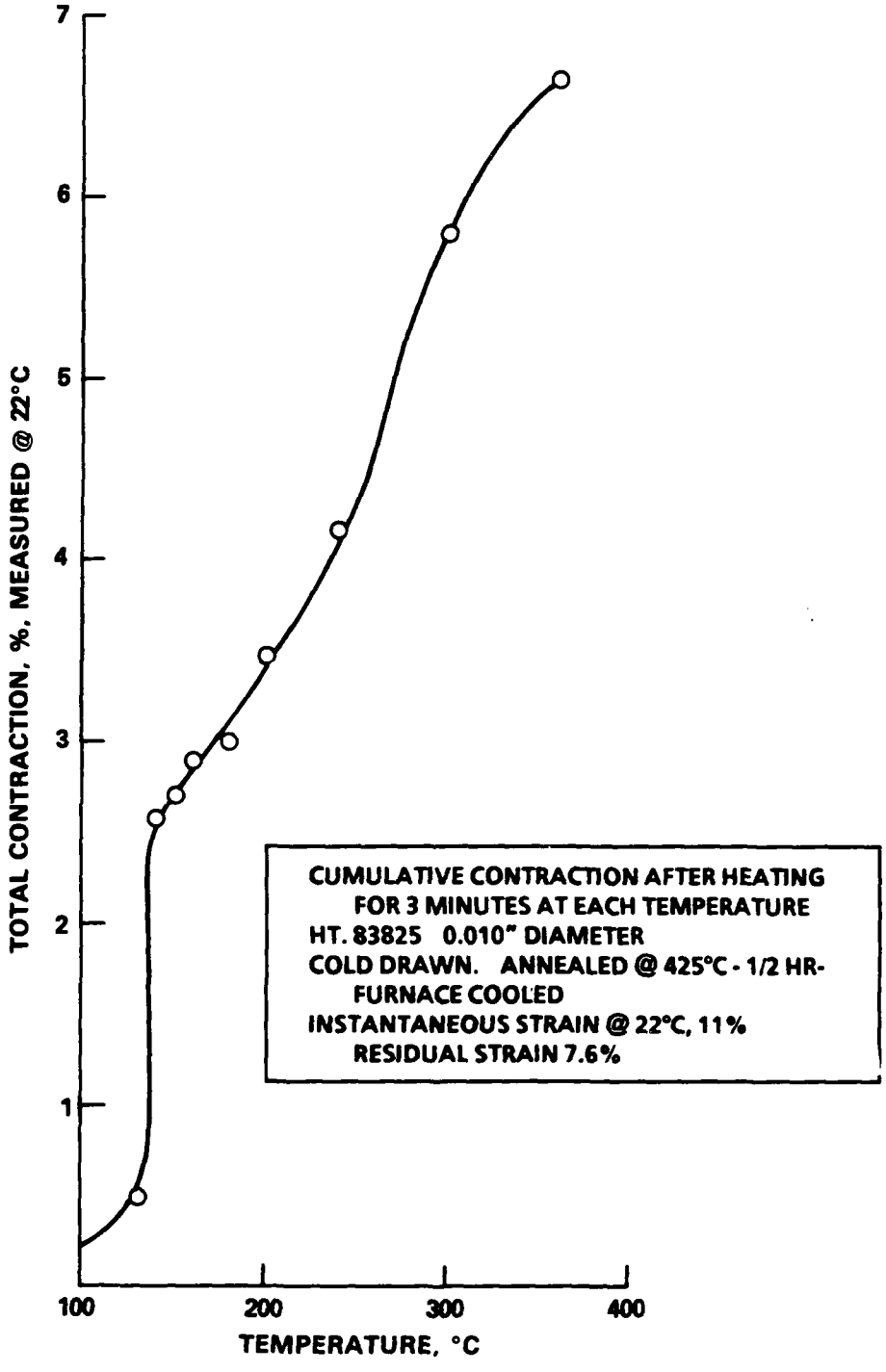



FIGURE 4. SHAPE RECOVERY (CONTRACTION) OF NITINOL WIRE VERSUS TEMPERATURE FOR SHORT TIME HEATING

Permanent strains can be quite stable for hundreds (even thousands) of transformation cycles.[8] (Such permanent strain may exist in both the austenite and martensite structures and is more properly the subject of a separate discourse. Also inappropriate for detailed review here is another strain value, the instantaneous one which exists during loading. It differs from the residual strain measured after unloading by the value of the elastic strain. Instantaneous strain is referred to in Figure 4 and Appendix A.)

Pre-strain is measured at room temperature with the load (stress) removed. Figure 5 shows the effect of pre-strain on transformation temperature, as determined by calorimetric sensing of the heat of transformation. With no pre-strain added, the transformation starts at 78°C, and completes at 94°C (see Figure 5(a)). A pre-strain of 11.5 percent increases the transformation temperatures to 149 and 159°C, respectively (see Figure 5(d)). Start and finish temperatures, taken from the graphs for the intermediate pre-strains, are given in Table 1. Further details concerning the transformation temperatures, including second heatings, are given in Appendix B.

The NITINOL wire does useful work during shape recovery, e.g., the lifting of a load. This load superimposes a strain on the pre-existing strains in the wire. Figure 6 shows the temperatures required for transformation as a function of the load lifted. Note that the added strain increases the start and finish temperatures of the transformation and also degrades the extent of the shape recovery.

The results of the interaction of the first and third kinds of strain with shape recovery are presented in Figure 7. Note that the residual and the work strains act in opposite directions, the former causing the wire to contract, and the latter causing it to extend. The higher-temperature (480°C) annealed wire has the lesser residual strain from drawing. Therefore, this wire is most affected by the 2.8 pound external load. The lower temperature (375°C) annealed wire has the greater residual strains and they are clearly dominant, producing the greater contraction, i.e., 3.5 percent versus 1.8 percent for the 480°C wire.

## ENERGY OF ACTIVATION

NITINOL is a low efficiency transducer of electrical into mechanical energy. When energy is ample, e.g., a tethered robotic device, this poses little problem. The S & A application, however, is of minimal size and weight, placing tighter strictures on the power supply. Despite its limited volume, the power supply must deliver adequate voltage and energy over a spectrum of ambient temperatures in a single short duration pulse. The voltage requirement stems from the relatively high resistance (approximately 75 micro-ohm centimeters) of NITINOL, about that of commercial resistance-heating wires such as Nichrome. The energy supplied raises the NITINOL to its transformation temperature, provides for its latent heat of transformation, and enables the useful work. The greatest portion of the energy is used in heating the wire to the transformation temperature. Therefore, in general, low ambient (starting) temperatures represent a greater demand for stored energy than does increased work to be performed. Single short duration pulses are desirable to minimize energy dissipation to the ambient environment by heat transfer.

An early approach in this work used capacitors as the stored energy source. A pair of very compact experimental capacitors connected in parallel, operating at

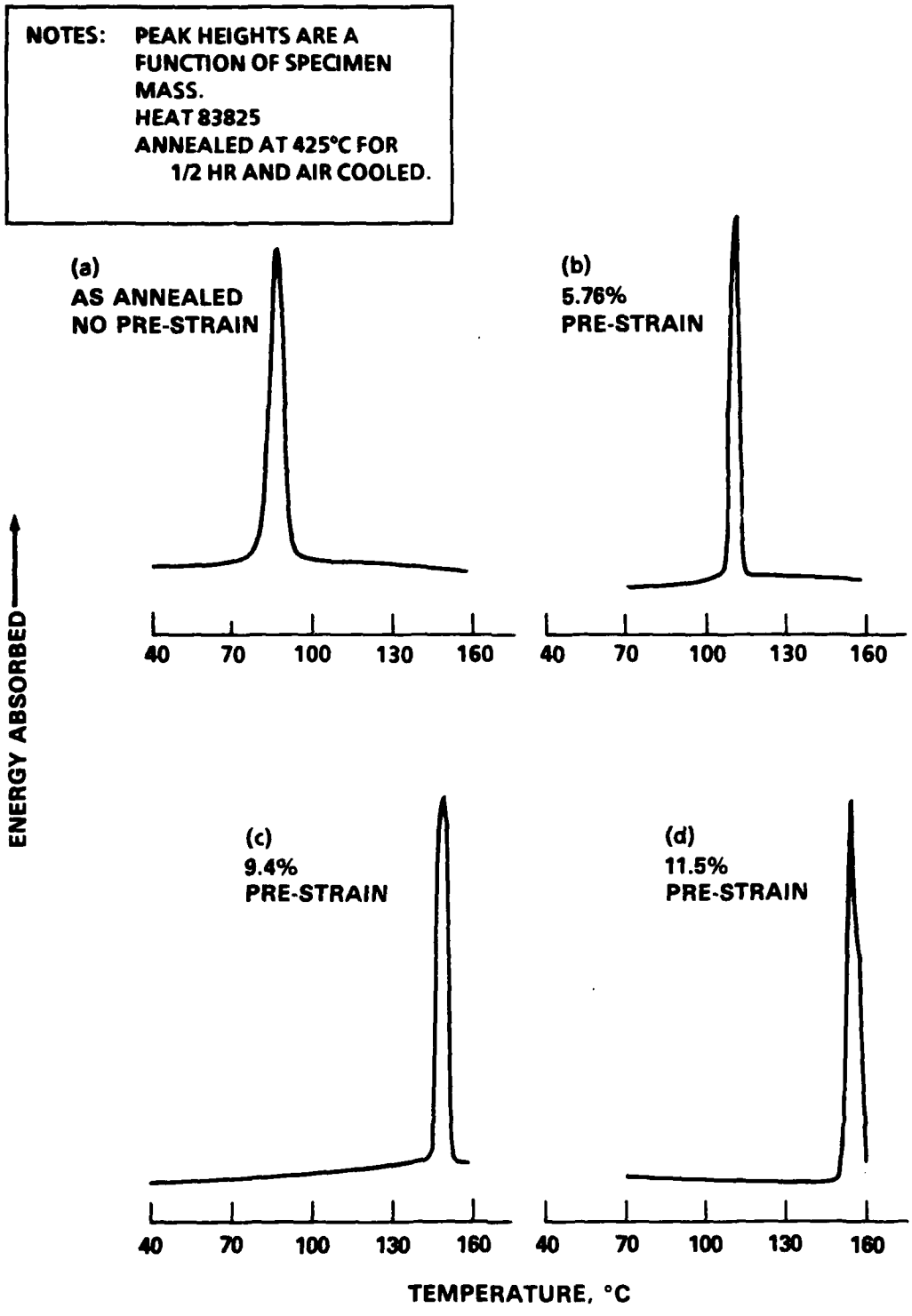



FIGURE 5. TRANSFORMATION TEMPERATURES OF PRE-STRAINED NITINOL DURING FIRST HEATING

TABLE 1. TRANSFORMATION TEMPERATURES OF PRE-STRAINED NITINOL DURING FIRST HEATING*

| PRE-STRAIN % | HEATING TRANSFORMATION | |
|---|---|---|
| | START, °C | FINISH, °C |
| 0 | 78 | 94 |
| 5.76 | 106 | 115 |
| 9.4 | 144 | 154 |
| 11.5 | 149 | 159 |

*HEAT 83825, ANNEALED AT 425°C for ½ HR. DATA BY DIFFERENTIAL SCANNING CALORIMETRY.

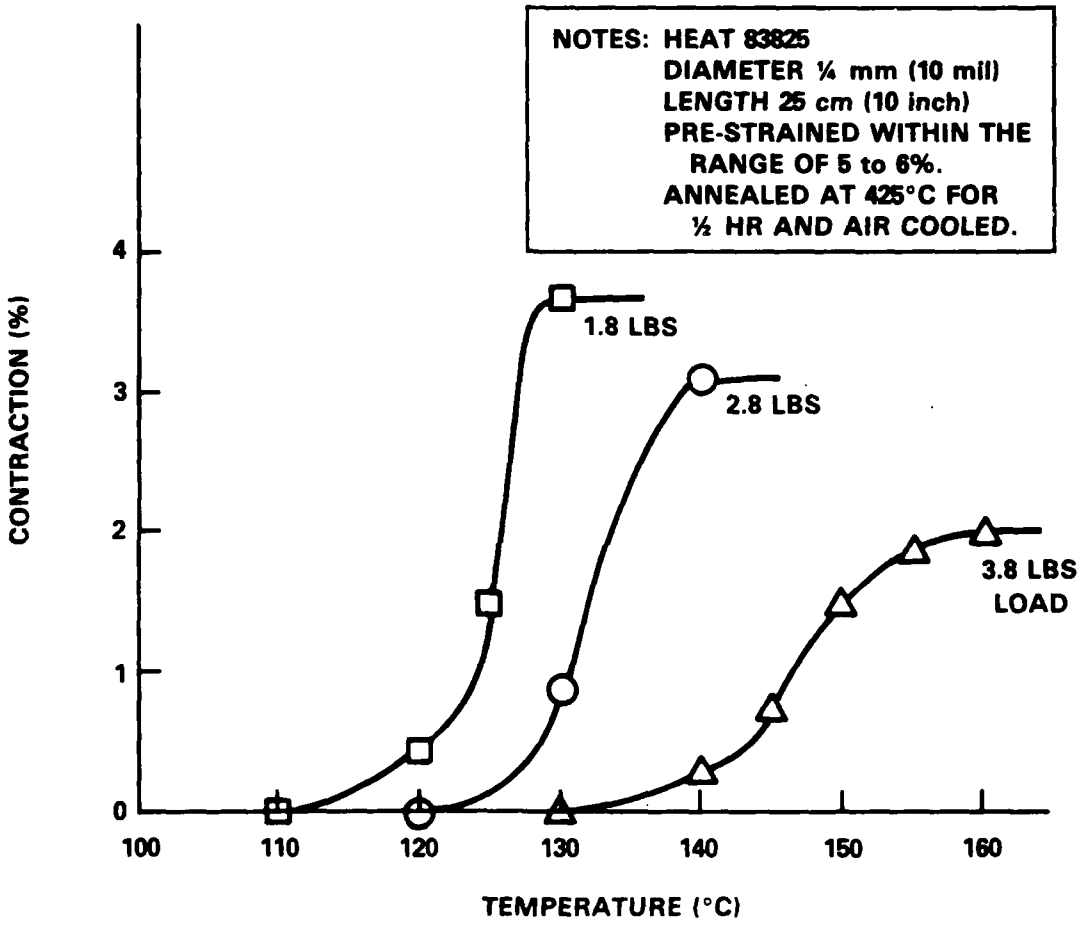



FIGURE 6. EFFECT OF APPLIED LOAD ON SHAPE RECOVERY OF NITINOL

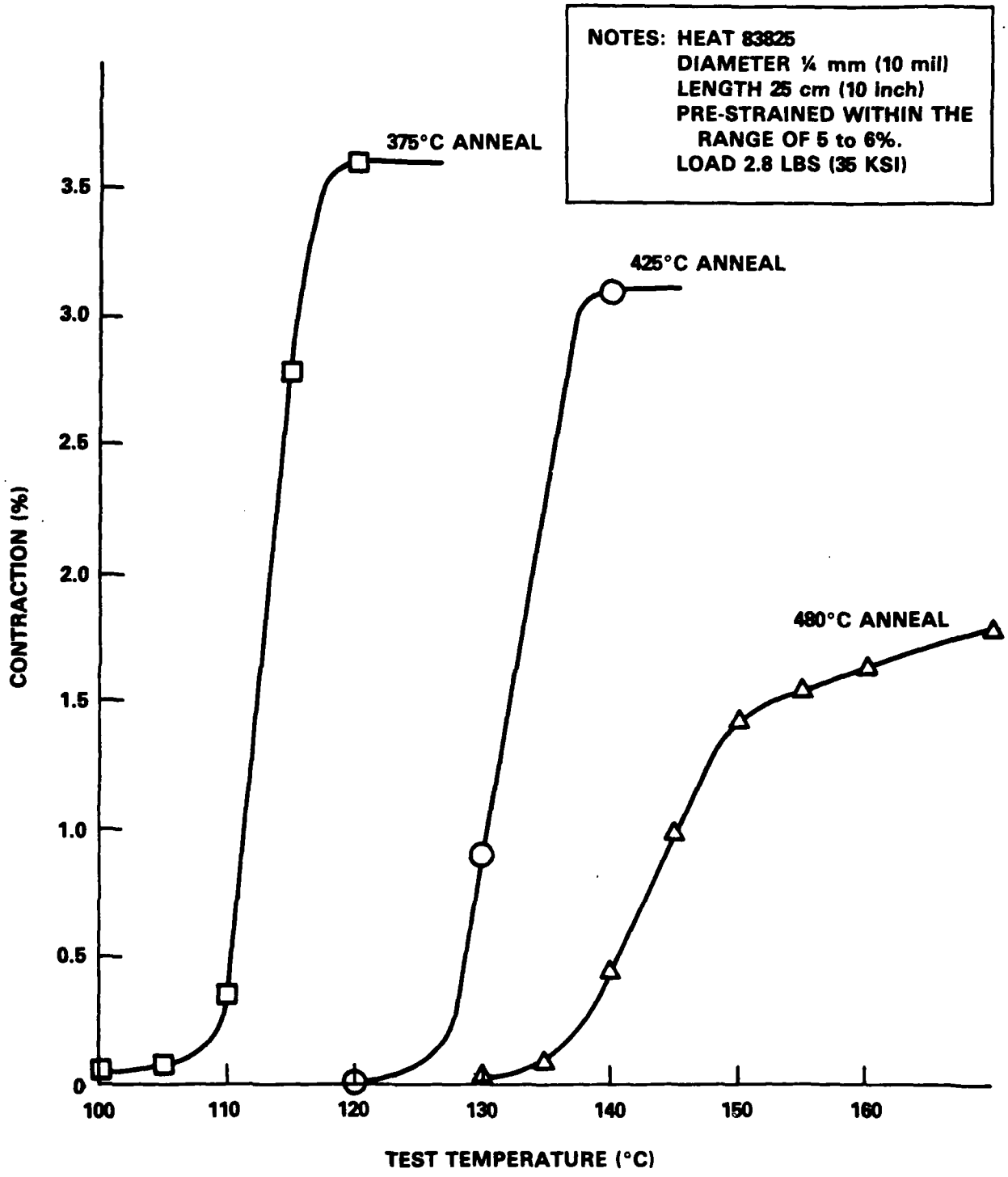



FIGURE 7. EFFECT OF PRIOR ANNEALING ON SHAPE RECOVERY OF NITINOL UNDER APPLIED LOAD

18 volts and 16 joules, were able to produce transformation in a 12 cm long, ¼mm diameter pre-strained wire. The performance was marginal due in part to internal electrical characteristics of the capacitors. Subsequently, a commerical electrolytic capacitor charged to the same voltage and energy, but of a much greater physical size, produced excellent transformations in wires under dead load, as also did pulses from a power supply. Since the latter provided measurable data its use was emphasized to determine the energy requirements for transformation.

Figure 8 shows the energy versus contraction data obtained in lifting loads of three different magnitudes. The electrical system of Figure 1 and the mechanical system of Figure 2 were used to generate these data. As expected, the energy requirement for a selected contraction value increases with the increased work performed. Figure 9 shows the dramatically decreased energy required as a consequence of increased residual strain.

The data presented in Figure 9, with the starting ambient of 20°C, indicate that a NITINOL wire of ¼mm diameter and 25 cm length can easily contract 8 to 10mm while exerting a force of 35 ksi (241 MPa). It will do this at 115°C or higher (see Figure 7). Activation temperatures up to 160°C are achievable with other combinations of load, contraction, and energy availability. Stored energy requirements for operations at 20 to 50°C (for both the battery and NITINOL) can easily be met by small commercially available batteries.

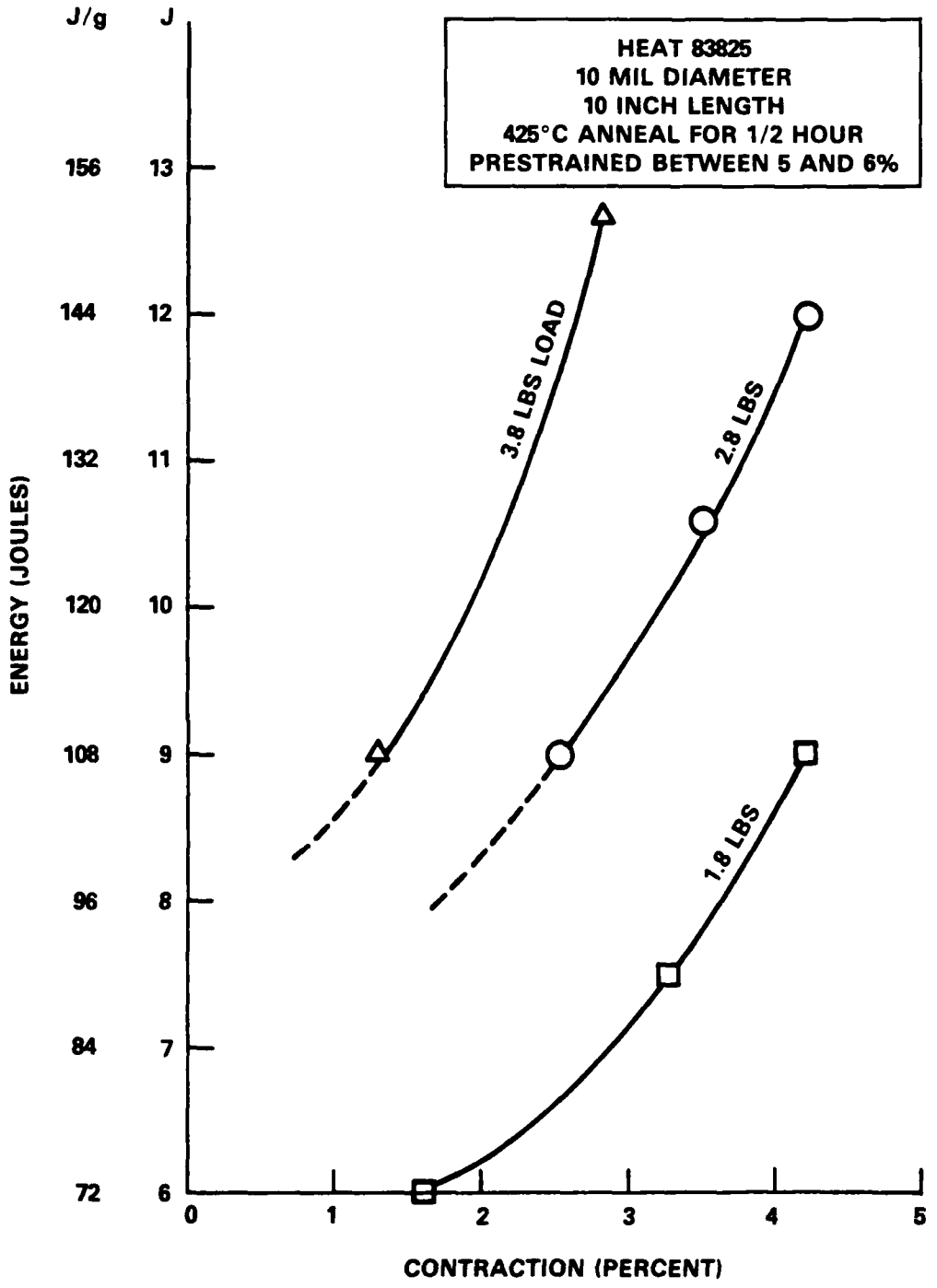



FIGURE 8. ENERGY TO TRANSFORM NITINOL UNDER LOAD

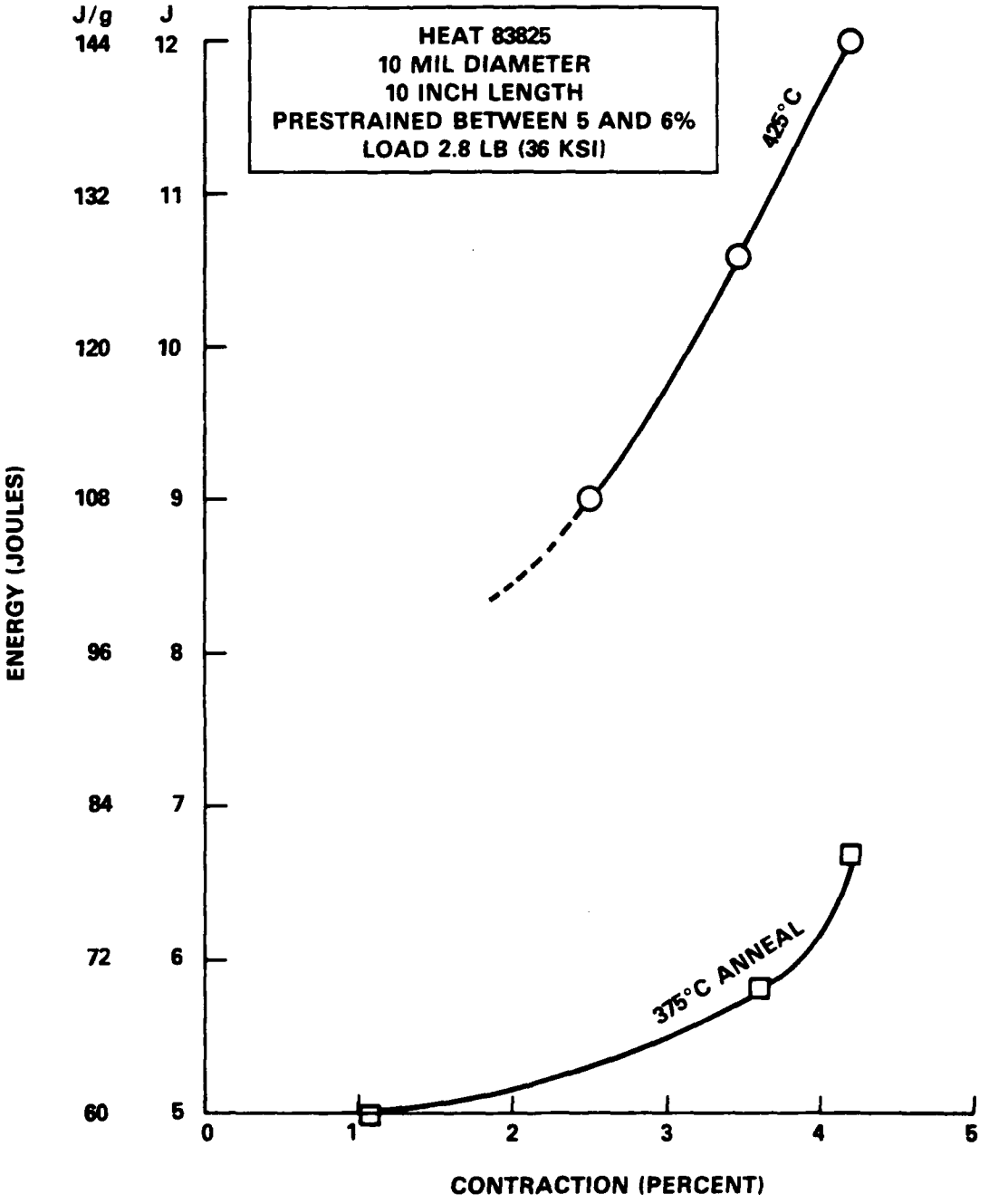



FIGURE 9. EFFECT OF ANNEALING TEMPERATURE ON ENERGY REQUIRED TO TRANSFORM NITINOL WIRE UNDER LOAD

## CONCLUSIONS

NITINOL shape memory alloy wire has the necessary attributes to function as part of an electrically actuated safing and arming component for fuzing explosives. Upon transformation, a 10 mil (¼mm) NITINOL wire will simultaneously exert a 35 ksi (241 MPa) stress and contract 3.5 percent in length. The electrical energy required for this transformation under load is 72 Joules per gram, starting from room temperature.

For a single (one time) usage, a NITINOL activation temperature can be selected between 115 and 150°C, depending on load and contraction requirements. The activation temperatures may be extended to as high as 360°C for sensing or activating under rapid heating conditions.

## RECOMMENDATIONS

Additional work should be performed to evaluate performance achievable with both battery and NITINOL actuating in sub-zero temperature environments.

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# APPENDIX A

## TEST PROCEDURE FOR PARTLY ANNEALED WIRE

The drawing of a wire leaves strains that vary from minimal at the center of the wire diameter, to maximum at the periphery of the wire. The annealing process mitigates or eliminates these strains, depending on time and temperature. It is usually desirable to retain some strain for good shape memory response. Residual strains can be detected by electrical resistance changes or by differential scanning calorimetry during cooling.

It is postulated that the martensitic transformation in NITINOL requires a perfect, or near perfect, austenite (B2) starting lattice. The prior drawing strain and the annealing treatment determine the extent of lattice perfection. The ability of some volumes of nominally perfect lattices to transform may be significantly affected by the stress exerted by nearby residually strained volumes. This influence acts during both the cooling and the heating legs of the cycle. Although the detailed transformation mechanics may be difficult to assess on a localized volume basis, a few annealing tests will predict shape recovery performance with reliability.

Prior processing of the wire, whose test data are shown in Figure 4 of the main body of the report, is presented here. Annealing of this lot of heavily cold drawn 10 mil diameter wire was done in an air furnace, with a high velocity fan providing uniform temperatures, within $\pm 2$°C of the set value. Very slight tension on the wire produced linear specimens. Following the treatment at 425°C for $\frac{1}{2}$ hour, the specimen was furnace cooled to 240°C and then air cooled. Sleeves were crimped to the wire ends and the distance between the sleeves measured as 10-7/8 $\pm$ 1/64 inch. The wire was refrigerated at -5°C for $\frac{1}{2}$ hour, and then uniformly strained in a tensile test machine at 22°C. The instantaneous strain was 11 percent, but the elasticity of the alloy reduced this to a residual tensile strain of 7.6 percent when the crosshead was unloaded.

The test specimen was enclosed in a 2 mil thickness stainless steel foil protective envelope and heated for 3 minutes at the consecutively higher temperatures shown, starting at 90°C. After each heating, the specimen was air cooled and the distance between crimp sleeves remeasured at 22°C.

# APPENDIX B

## MODIFIED TEST PROCEDURE FOR DIFFERENTIAL SCANNING CALORIMETRY

Differential scanning calorimetry (DSC) senses the heat absorbed by NITINOL during heating. The peak heights shown in Figure 5 of the main body of the report are a function of specimen mass, which is usually 30 milligrams or less. This test was performed on Heat 83825 wires that were hard drawn to 21 mils, annealed at 425°C for ½ hour, refrigerated to −5°C, and stressed to produce the residual pre-strain reported. During heating, the specimens in DSC transform under no-load conditions.

The usual DSC test procedure is to heat the specimen to +130°C, which is above its transformation temperature. This provides a fully austenitic structure to begin the recording of transformation temperatures during cooling. During the subsequent heating from −130°C, the heating transformation temperatures are then recorded. This procedure was reversed to determine the first-time heating transformation temperatures (Table 1 of the main body of the report). The significant shift in transformation temperatures for second versus first heating, as detected by electrical resistance, was reported earlier.[B-1] The transformation temperatures obtained on this wire for the "usual" and the "reversed" DSC test method are shown in Table B-1. Strain has an effect on the transformation temperature for the second-time heating of NITINOL, but its effect on the first heating is far more pronounced.

[B-1] Goldstein, D., "Nitinol Strain Effects," J. of Metals, Sep 1987, pp. 23-27.

TABLE B-1. TRANSFORMATION TEMPERATURES OF PRE-STRAINED NITINOL DURING FIRST AND SECOND HEATING*

| PRE-STRAIN % | HEATING TRANSFORMATION TEMPERATURE (°C) | | | |
|---|---|---|---|---|
| | START TEMPERATURE | | FINISH TEMPERATURE | |
| | FIRST CYCLE | SECOND CYCLE | FIRST CYCLE | SECOND CYCLE |
| 0 | 78 | 73 | 94 | 90 |
| 5.76 | 106 | 72 | 115 | 87 |
| 9.4 | 144 | 84 | 154 | 98 |
| 11.5 | 149 | 91 | 159 | 105 |

*HEAT 83825, ANNEALED AT 425°C - ½ HR. DATA BY DIFFERENTIAL SCANNING CALORIMETRY.

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